UNCLASSIFIED

CRATERING AND PENETRATION

by

E. P. Palmer

Fourth Quarterly Program Progress Report
Contract AF 04(694)-259

30 June 1963

Prepared For

AIR FORCE BALLISTIC SYSTEMS DIVISION

AIR FORCE SYSTEMS COMMAND

Norton Air Force Base, California

UNCLASSIFIED

HIGH VELOCITY LABORATORY
DEPARTMENT OF ELECTRICAL ENGINEERING
UNIVERSITY OF UTAH
SALT LAKE CITY, UTAH

UNCLASSIFIED

CRATERING AND PENETRATION

by

E. P. Palmer

Fourth Quarterly Program Progress Report
Contract AF 04(694)-259

30 June 1963

Prepared For

AIR FORCE BALLISTIC SYSTEMS DIVISION

AIR FORCE SYSTEMS COMMAND

Norton Air Force Base, California

UNCLASSIFIED

SUMMARY

This quarterly report covers experimental and theoretical work done under Contract AF 04(694)-259 during the period 1 April to 30 June 1963. The goal of the work is to develop general theoretical models of the behavior of thick targets and one- and two-layer thin targets under hypervelocity impact.

Progress is reported in five areas as follows:

1. Energy Partitioning in Impact. Theroetical studies were made to estimate residual shock heating produced in a target for flat-plate and projectile impact. Preliminary measurements indicate that shock heating does not account for the observed temperature distribution.

2. Transient Measurements in Cratering. A project to measure wave transients in cratering by means of buried pressure transducers has been completed and a report prepared. The report is Technical Report UU-13, Stress-Time Measurements in High-Velocity Impact, by S. M. Taylor, E. P. Palmer, and R. R. Kadesch. An abstract is included. It was found that significant information can be obtained on stress levels, wave profiles, and wave velocities for elastic and plastic waves.

3. Wave Motion in Impact. The theoretical study of wave motion in thin plates has continued. Experimental work was initiated to obtain precisely controlled impact of small, thin-plate projectiles.

4. Material Properties. Various equations for describing material properties for expansion processes in metals are being investigated for use in the wave equations and in impact models.

5. Cratering and Penetration. Work has continued in applying the results of the above studies to the development of a theoretical model for thin-target penetration. An experimental program to measure surface displacement in penetration has been initiated. This should allow measurements of surface waves and material flow to be made.

TABLE OF CONTENTS

1. INTRODUCTION

The purpose of work done under Contract AF 04(694)-259 is to develop theory describing the phenomena which occur during hypervelocity impact. The desired theory must be general enough to include all phenomena of importance in target damage and spray-particle generation and must be applicable to a wide variety of materials and conditions. The behavior of single and two-layer thin targets is of particlular interest.

Past work in this laboratory has concentrated on investigations of cratering in semi-infinite metal targets. The understanding of material properties and behavior gained in these studies is of general application to any impact problem. Some of this work is continuing, particularly in the area of energy measurements, but the emphasis of present theoretical and experimental work is on thin-target impact.

The plan of investigation used in this research has been to begin with simple idealized models which illustrate various phases of the problem and to study their behavior experimentally and theoretically. These models are then modified and combined in the formulation of more comprehensive models.

In carrying out this program, work is being done, and progress will be reported, in five areas as follows:

1. The investigation of energy partitioning in impact and the development of theory based on this.
2. The development of instrumentation for observing transient behavior in impact.

3. The investigation of wave propagation in various systems and materials of interest in hypervelocity impact.
4. The investigation of material properties and the formulation of suitable mathematical descriptions of material-property behavior.
5. The formulation and solution of models describing the overall impact process being considered.

2. ENERGY PARTITIONING IN IMPACT

This project is concerned with determining the distribution of energy among the various competing processes occurring in cratering and penetration and with determining the effects of different material properties, geometry, and impact velocity on this energy distribution. The purpose is to provide information necessary to formulate impact theory from models which adequately describe the physical processes involved.

Theoretical Investigation of Shock Heating. At the Sixth Hypervelocity Impact Symposium, discussions were held with R. L. Bjork, A. E. Olshaker, and J. M. Walsh concerning the relationship between our energy-distribution measurements and their hydrodynamic model of cratering. No final conclusions could be reached because no target-heating computations have been made using their model, and our measurements are for a different material and a different velocity regime. However, it was agreed that a problem exists because the only mechanism causing target heating, in their model, is irreversible shock heating and this appeared to be inadequate to explain the heating observed in our experiments where velocities and shock strengths are low.

To elucidate this problem, the shock-heating data from Los Alamos[1] were used in two simplified models to compute expected target heating. As a preliminary, the heat energy remaining in a metal (lead) after isentropic expansion from a shock compression was compared with the kinetic energy and internal energy (assumed to be equal) of the compressed material. The results are shown in Fig. 1 which indicates that the energy appearing as heat E_h is approximately a constant fraction of the internal energy E_s

$$E_h \approx 0.14\ E_s$$

This greatly simplfies the calculation of shock-heating effects. It is of interest to find whether this linear relationship applies to other metals and nonmetallic materials. This will be done as the need arises in the future.

An analytical expression relating shock pressure and internal energy was desired. Plotting these two variables as shown in Fig. 2 indicates that an exponential relationship exists as follows for the pressure range of interest

$$E_s = A\ p^b$$

For lead, $A = 1.253 \times 10^{-8}$ and $b = 1.5164$ for E_s in erg/g and p in dyne/cm^2.

---

[1] R.G. McQueen and S.P. Marsh, Jour. Appl. Phys., Vol. 31, p. 1253, 1960.

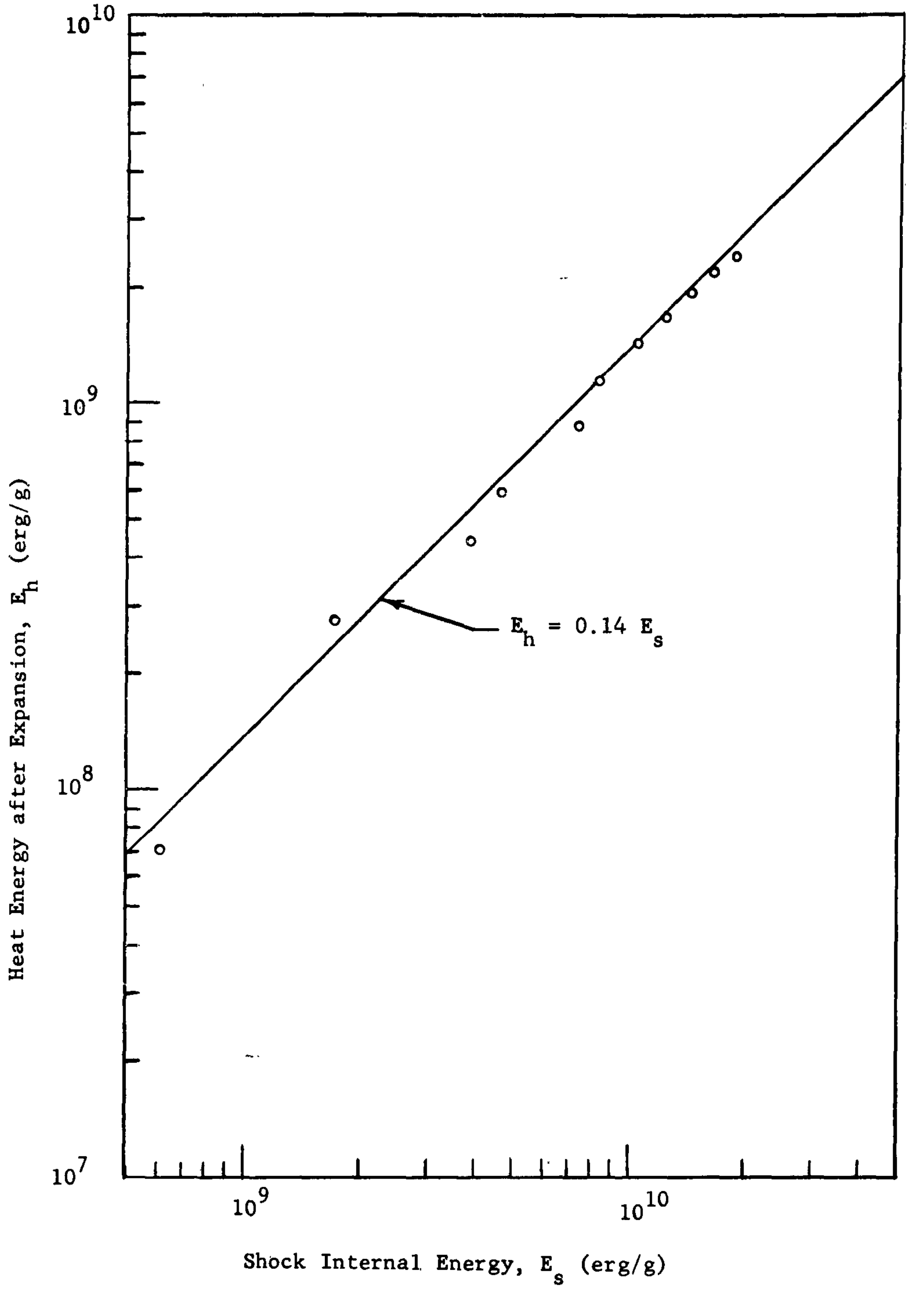


Fig. 1. Energy appearing as heat after passage of a shock wave, E_h, plotted versus internal energy behind the shock wave, E_s, for lead. The points are computed from Los Alamos data.

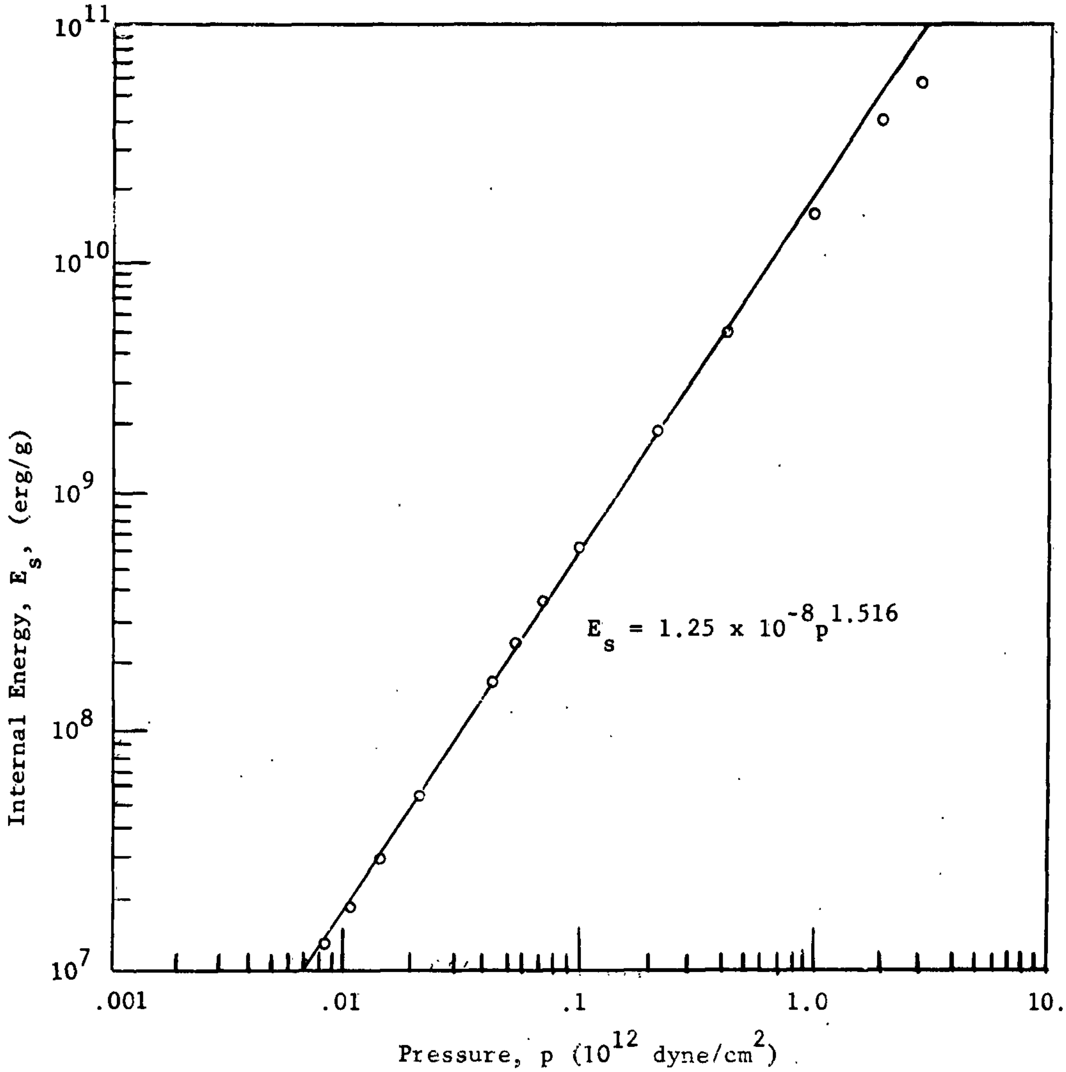


Fig. 2. Internal energy versus pressure for a shock wave in lead. The points are computed from Los Alamos data and the straight line is for the equation $E_s = Ap^b$ assumed valid up to 0.5 megabar.

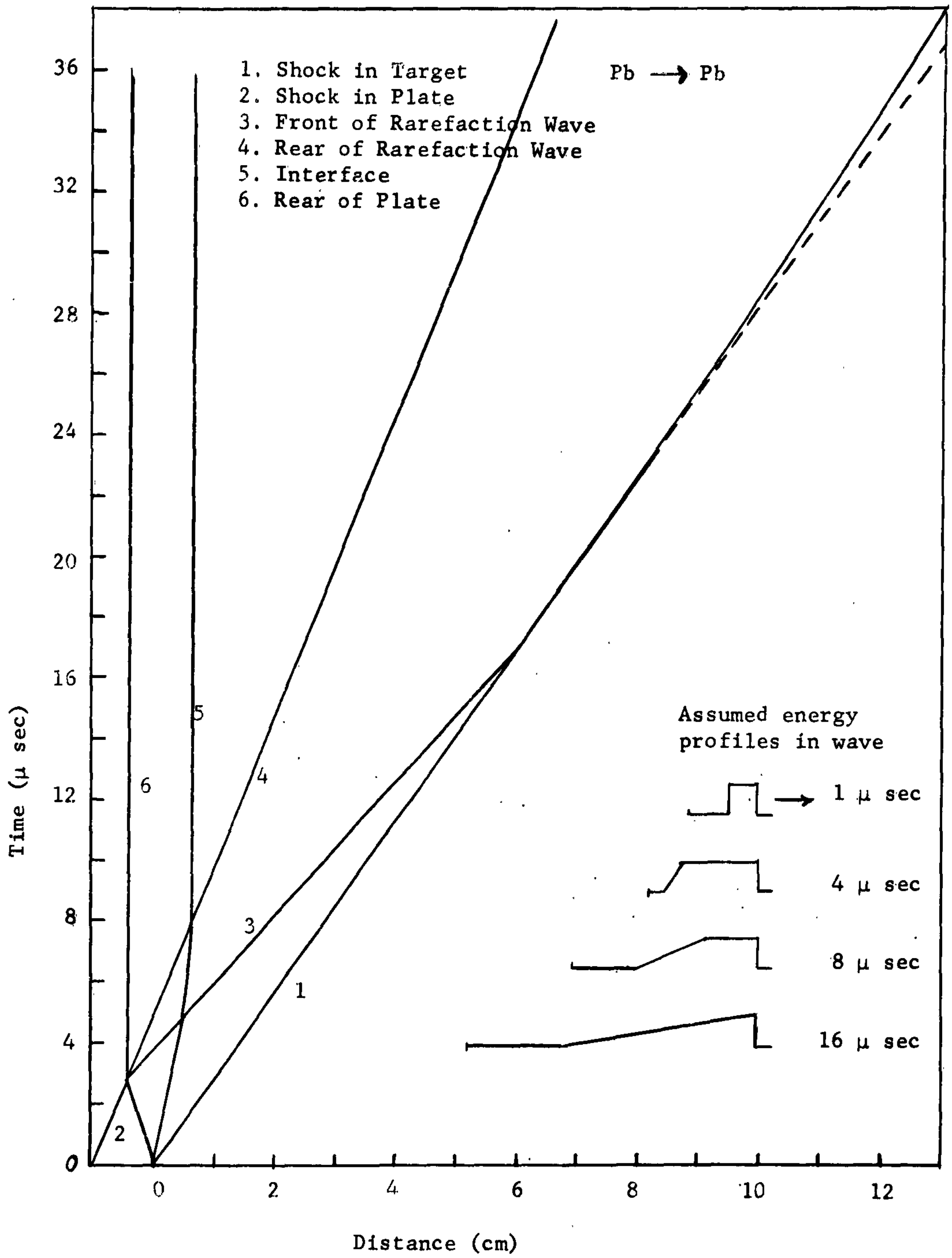


Fig. 3. Distance-time plot for waves assumed for impact of a flat plate on a semi-infinite target. Impact velocity 2 km/sec.

Using these material properties, an approximate model of wave motion for impact by a flat plate was examined for target heating. The energy pulse shape assumed and the first approximation for a time-distance plot are shown in Fig. 3. In this first approximation, energy losses were neglected and the area under the pulse curve was held constant. The resulting target heating plot is shown in Fig. 4. The main effect of

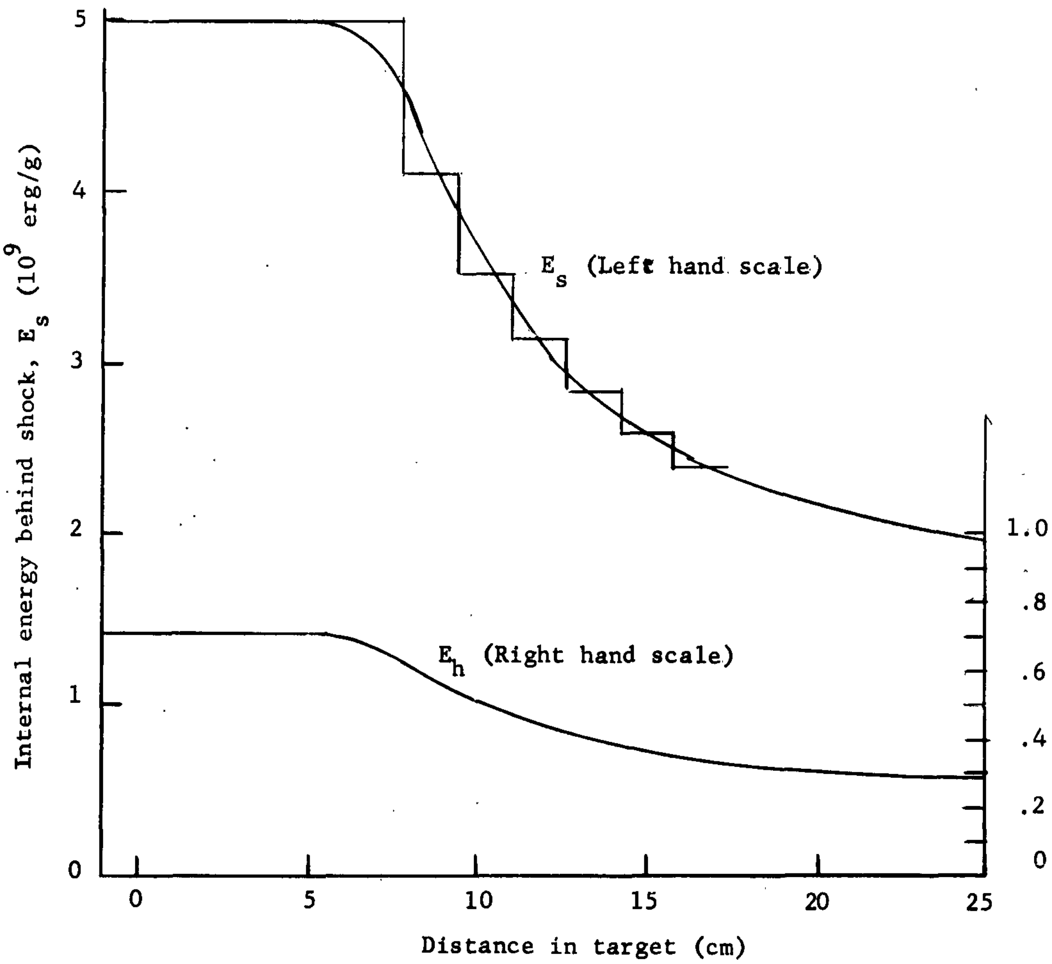
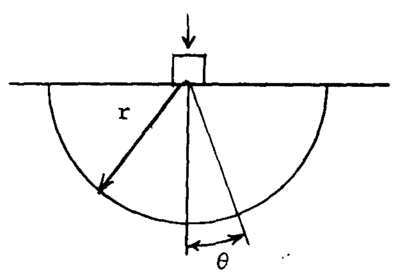


Fig. 4. Shock-wave heating for impact of a 1 cm thick lead plate on a lead target at 2.0 km/sec.

including energy losses and making a more exact calculation would be to cause the energy to decay more rapidly after the rarefaction overtakes the shock front. The plate energy was 2.26 x 10'' erg/cm^2. The graph shows that about half of this energy is dissipated as heat in the first 15 cm and about half of the remainder in the next 15 cm.

A model which may better illustrate conditions in cratering was formulated by assuming that in the case of impact by a projectile, the pressure wave decays as 1/r, where r is the distance from the impact point and that the pressure around the front is proportional to cos θ.



This model has reasonable theoretical justification because for constant energy in the wave front, pressure will decrease as 1/r for a linear material. In the actual case, the energy at the front will be reduced by the rarefaction wave from the rear of the projectile. This will cause a faster pressure decay than 1/r after a time comparable to that found in the plane-wave case. Also, flow and nonlinear material effects will cause the pressure to decay faster than 1/r. Experimental justification for the model comes from measurements of the pressure field for impact in water where the 1/r law is obeyed. The existing measurements in metals do not contradict this pressure law but are not accurate enough to establish it. The justification is adequate for the purposes of this model.

Using the pressure decay law and the relationship between pressure and heating, the energy appearing as heat was calculated for the impact of a projectile 1 cm in diameter and 1 cm long impacting at a velocity of 2 km/sec. The energy per unit mass appearing as heat is plotted versus distance into the target in Fig. 5. The integrated energy loss is plotted in Fig. 6. In the actual case, the energy would decay somewhat more rapidly with distance than is indicated here because of the effects mentioned above.

In this example, the projectile energy is 1.43×10^{12} erg. It is seen that this energy is about half dissipated in a distance of 15 to 20 cm. Measurements of target temperature distribution discussed below, and previous measurements made to test the validity of using a target as a calorimeter, indicate that in an actual impact of this nature, almost all the energy is dissipated in a distance of 10 cm and about 60 per cent of this appears as heat.

No final conclusions can be drawn by comparing these approximate calculations with preliminary measurements; however, the indication is strong that other mechanisms exist for dissipating energy which are comparable in magnitude with shock heating. At higher velocities, shock heating may predominate, but this is uncertain now and is worthy of careful investigation.

Measurements of Energy Partitioning. Thus far in this study most concern has been with three general categories into which the kinetic energy of the projectile is divided during cratering. These categories

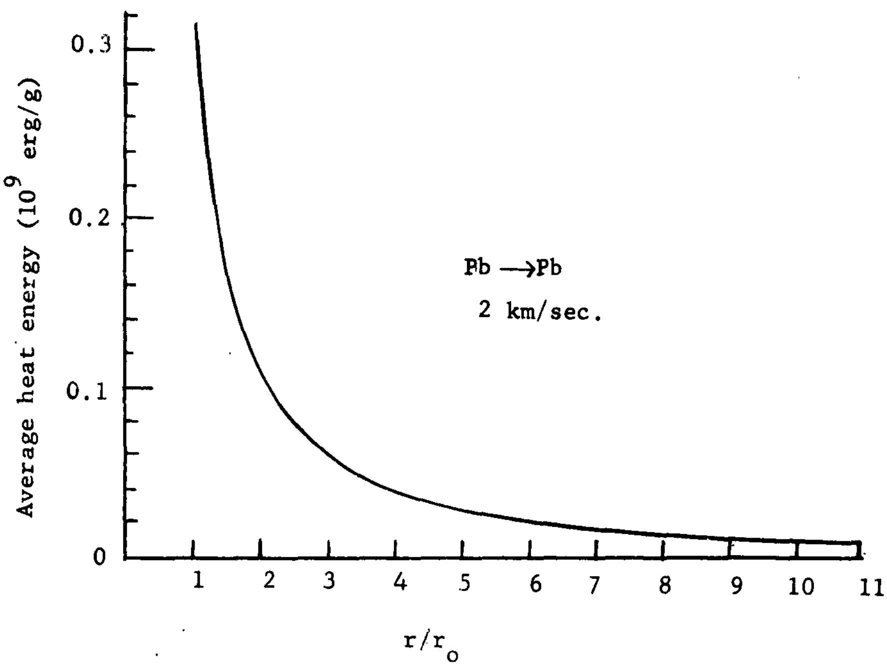


Fig. 5. Energy per unit mass appearing as heat averaged over the hemispherical wave front. r is distance from impact and r_o is projectile radius.

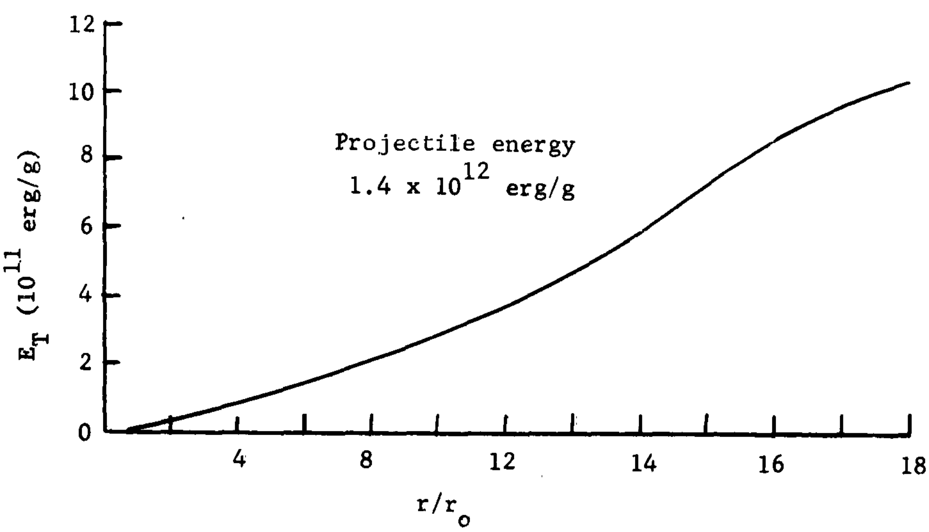


Fig. 6. Integrated total energy loss, E_T, appearing as heat for impact of 1 cm-diam, 1 cm-long lead projectile into a lead target at 2.0 km/sec.

are:

1. Energy used in heating the target.

2. Energy associated with spray particles.

3. Energy associated with recrystallization of the target material.

Previous progress reports describe methods by which the amounts of energy going into each category have been determined and contain data showing these values. These data have not previously been compared with each other and with total projectile energy. Such a comparison is made here as shown in Fig. 7. Ideally, the sum of the energy in the three categories should equal the kinetic energy, assuming that energy is not used in any other process. However, there is too little energy accounted for at lower velocities and too much accounted for at higher velocities. This variation, assumed to be experimental error, does not exceed ten per cent.

In these studies, the target material has been lead in which recrystallization of stressed material takes place easily at room temperature. Most other metals recrystallize easily only at higher temperatures. In these materials the energy which is here called recrystallization energy would be in the form of locked-in stresses rather than recrystallization.

Figure 8 shows the same relationships shown in Fig. 7 except that the data have been normalized so that the sum of the three categories equals the projectile kinetic energy at all impact velocities. This plot illustrates the approximate relationships among the three categories as determined by experimental techniques.

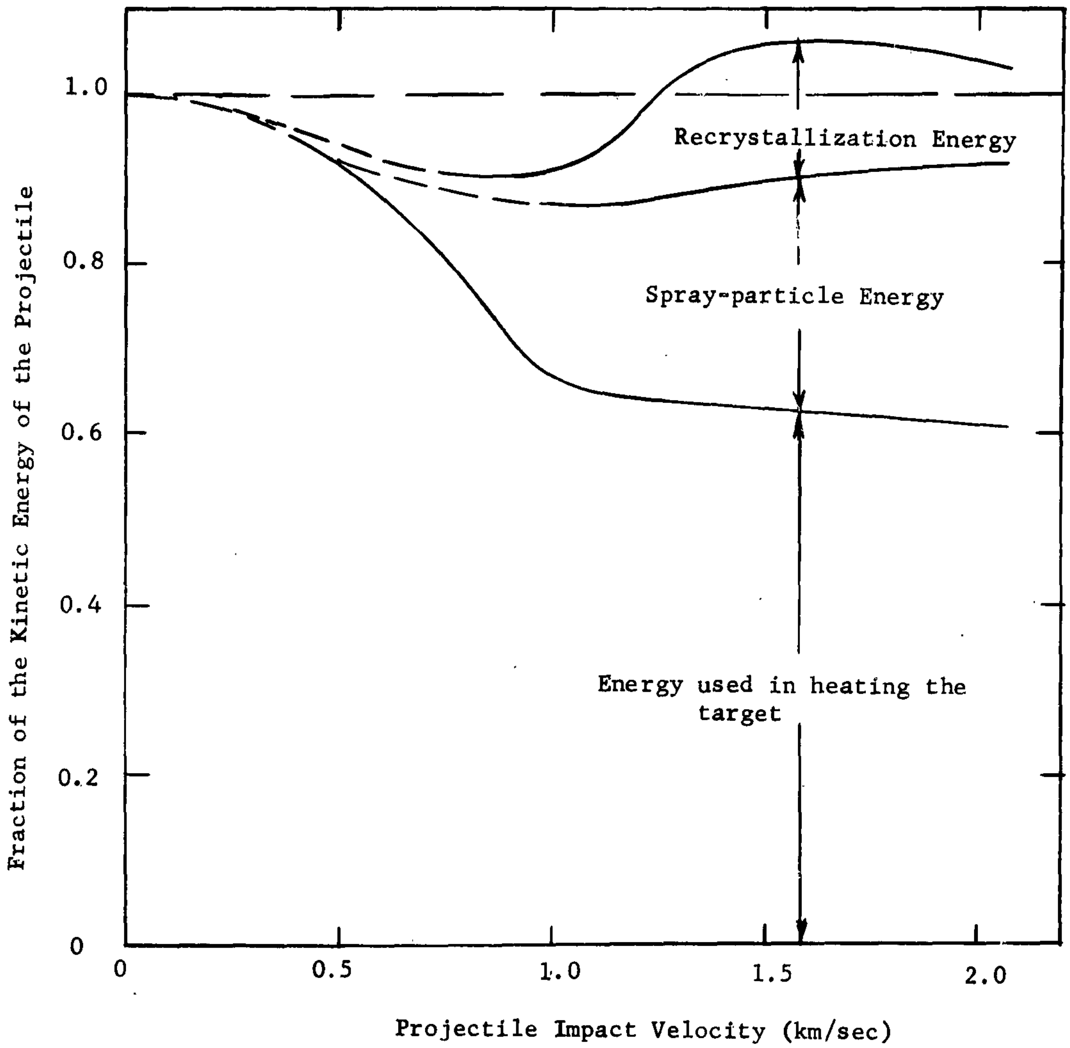


Fig. 7. Plot showing the partitioning of energy at velocities up to 2.0 kilometers per second for the impact of steel balls into lead.

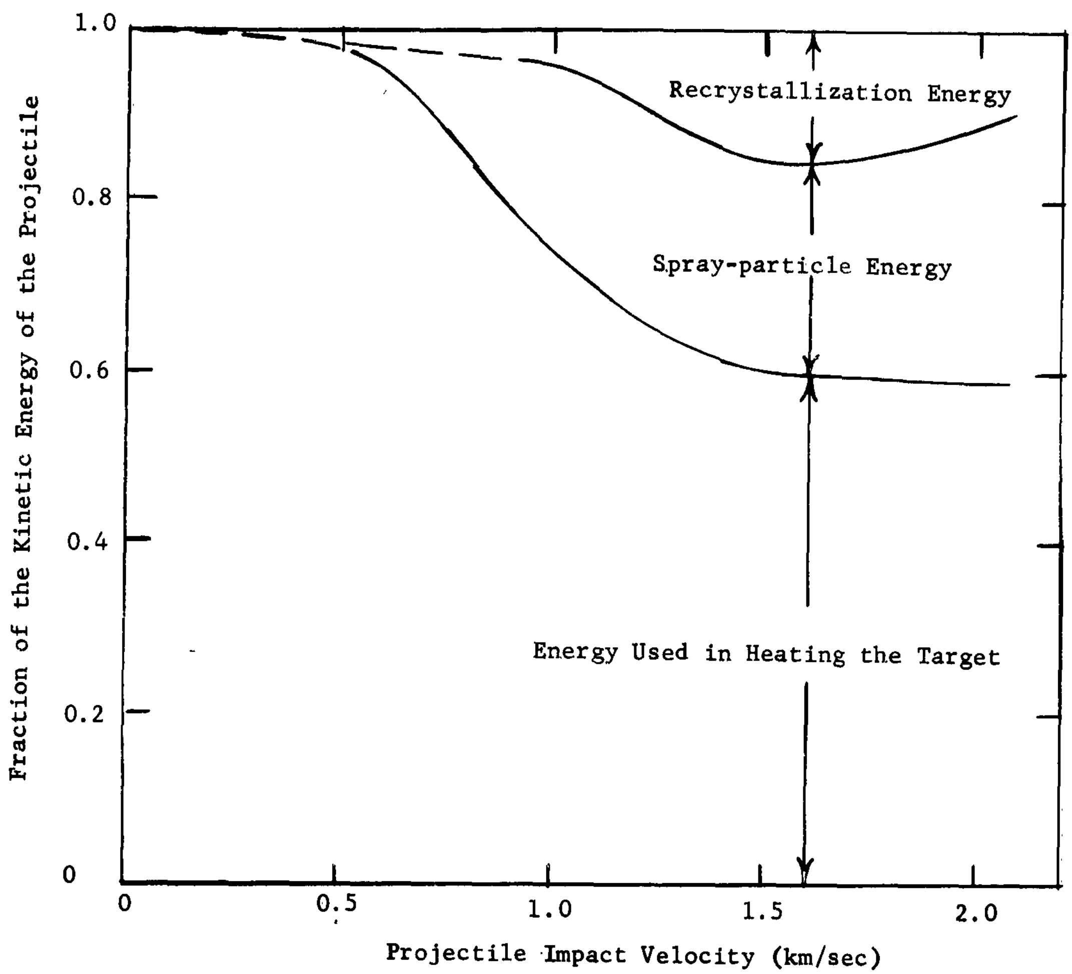


Fig. 8. Normalized plot showing the partitioning of energy at velocities up to 2.0 kilometers per second for impact of steel balls into lead.

The method used to determine the energy associated with spray particles consisted of catching the spray particles in a lead box and measuring the temperature change of the box. This gave a measure of the total energy of the spray particles. No determination has been made of the fraction of the energy due to velocity and the fraction due to an increase in temperature and little is known about either velocity or temperature. It was felt that some means of measuring the temperature of the surface of a crater as it is being formed would be of value in explaining cratering and spray-particle formations. A detector to do this would require a fast response to temperature changes and would have to maintain contact with the crater walls throughout the cratering process. Various ideas have been considered. Some work has been done by other investigators in measuring transient temperatures in which various types of temperature indicators have been used. Moeller[2] describes thermocouples having a short response time which were used in measuring transient surface temperatures of machine-gun barrels during firing. However, these investigations did not involve a moving surface such as occurs in crater formation.

A preliminary procedure for measuring crater-wall temperature has been outlined as follows:

1. Drill a small hole in a lead target as shown in Fig. 9a.
2. Place two insulated wires, one iron and the other constantan, in the hole and pot them with epoxy.

[2] Temperature, Reinhold Pub. Corp., Vol. 3, pt. 2, p. 617-623.

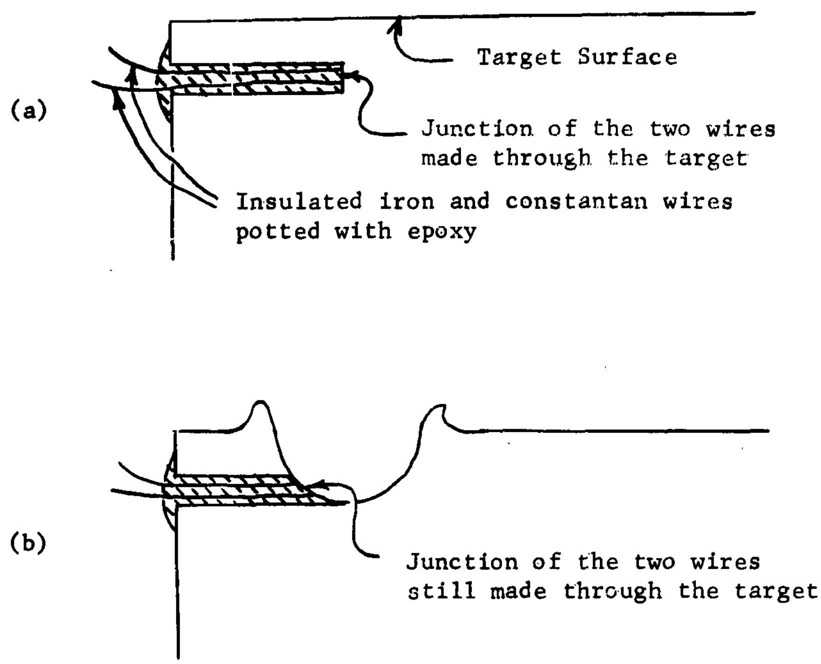


Fig. 9. Sketch showing:
a. Placement of iron-constantan thermocouple in a lead target to measure crater-wall temperature.
b. The target after formation of the crater.

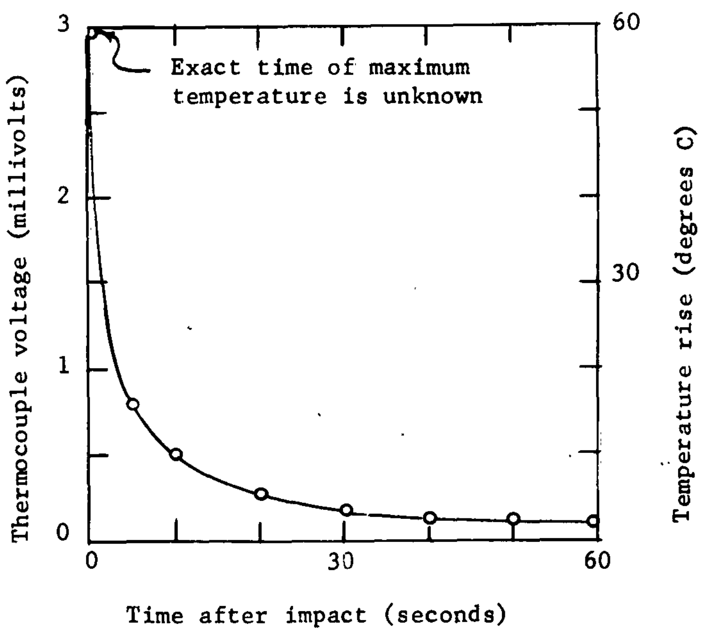


Fig. 10. Plot of thermocouple voltage and temperature rise as function of time after impact of the projectile.

3. Hook the two wires in series with a temperature reference thermocouple embedded in a separate block of lead.
4. Impact a projectile into the target above the embedded wires so that as a crater is formed it passes through the holes containing the wires as shown in Fig. 9b.
5. As the crater grows in size, contact between the two wires is maintained at the crater wall. The thermocouple out-put voltage gives an indication of the crater-wall temperature.

Following this procedure, four preliminary shots have been made. The results are encouraging although inconclusive. One shot was made at a velocity of 1.7 km/sec. In this shot the epoxy plug was blown from the target. The plugs, although loosened, remained in the target in the other three shots which were all at about 1.2 km/sec. This indicates that a better method will have to be devised to hold the wires in place. The holes in which the wires were placed about 5/32 inch in diameter. Smaller holes will probably give better results. In the three shots at 1.2 km/sec, maximum thermocouple readings of about three millivolts were observed. This indicates a temperature increase of 60 degrees centigrade. Figure 10 is a plot of thermocouple voltage and temperature increase as functions of time after impact for one of the shots.

The size of wire used in these initial shots was 24 awg and the wires were insulated with plastic tubing. This gave a rather bulky arrangement which prohibited easy erosion of the wires by the cratering action and made electrical contact between the two wires somewhat uncertain. Use of smaller wires with thin insulation will probably give better results.

For a shot at 1.2 km/sec, a rough calculation of the thickness of the heated lead adjacent to the crater indicates that a shell having a thickness of 0.4 centimeter would be involved. This is approximately the thickness of the deformed region of a similar crater as observed in an etched section. It is difficult to predict just how accurate these temperature measurements can be since high pressures affect the output of thermocouples. It is assumed that pressure effects will be of short duration and that reliable temperature readings can be made after they pass.

In the measurements made so far, thermocouple voltages have been determined by visual observation of a micro-volt meter. Future measurements will be attempted by direct coupling of the thermocouple circuit to an oscilloscope. If this can be done, much more accurate time and temperature measurements will be obtained.

Extending Energy Measurements. Figures 7 and 8 indicate the importance of extending energy measurements to higher velocities. It appears that the fraction of energy going into recrystallization decreases and that spray energy and heat energy may remain relatively constant. This must be tested because of the theoretical value of the results and the fact that the velocity range of primary interest is well above the present measurements. During this report period, considerable effort has been put into the light-gas gun, so that the data can be extended. A new high-pressure section has been designed and machine work is essentially completed. A diaphram testing device has been built. It is expected that data shots can be obtained during the final quarter of the contract.

3. TRANSIENT MEASUREMENTS IN IMPACT

This project is concerned with developing techniques and instrumentation for observing transient phenomena occurring during impact.

During this quarter, a project to measure subsurface pressure waves during impact by means of buried transducers was completed and a report prepared. An abstract of the report, which is being submitted for approval and assignment of an AFBSD-number, is included here. The techniques developed in this work are now being applied to studies of wave motion in thin plates.

Abstract of Technical Report UU-13, Stress-Time Measurements in High-Velocity Impact by S. M. Taylor, E. P. Palmer, and R. R. Kadesch.

A new method for the measurement of stress-time effects in high velocity impact is outlined. A technique for mounting small barium titanate piezoelectric transducers within semi-infinite aluminum targets is described. The targets are impacted by spherical projectiles of the same material as the target. The projectiles were accelerated to velocities ranging from approximately 0.1 km/sec to 2.0 km/sec. The electronic circuitry developed to acquire information from the transducing elements is presented. The use of isotropic elastic theory in the analysis of the data thus obtained demonstrates that the experimental technique is, in fact, a suitable method for the measurement of these phenomena. It is demonstrated that the method will give significant information about wave propagation and stress levels in elastic and plastic waves. Further application of the system should provide more satisfactory information about the intricate, but still largely unknown, processes which attend the formation of craters in semi-infinite targets.

4. WAVE MOTION IN IMPACT

The transport of energy in the impact region by means of wave motion is of fundamental importance in impact phenomena. A program of theoretical and experimental investigation of wave motion for a variety of materials and for various impact geometries has been undertaken. The goal is to provide basic understanding necessary for the formulation of accurate theoretical models of the overall cratering and penetration process.

During this quarter, theoretical work continued on the analysis of plane waves in thin, single targets and in two-layer targets. The report summarized in the Third Quarterly Report will be delayed to include experimental data and an analysis of specific systems. It will be included in the final report on the contract.

Experimental work during the quarter consisted of the design, construction, and preliminary testing of a track and velocity measuring system to hold projectiles in exact orientation before impact and to measure their velocity just prior to impact. The system appears to work well. Its purpose is to provide controlled impacts by cylinders of 1/2 inch diameter with lengths ranging from 1/32 inch to 3 inches. Instrumentation of the target with barium titanate pressure transducers is being investigated and methods of temperature measurement in the projectile are being considered.

5. MATERIAL PROPERTIES

The goal of this project is to be able to describe material properties under conditions met in hypervelocity impact by general mathematical expressions instead of by tables of numerical data. With simplified descriptions of material properties, more complex processes may be successfully investigated.

During this quarter, the behavior of metals in an expansion process was investigated more fully. It was concluded that the equation $u/pv = m\,u^k$, where u is internal energy, p is pressure, v is specific volume, and m and k are constants, is related to the process involved. It describes the compression process adequately but fails to describe the expansion process. Investigation of this and related equations is continuing actively.

A preliminary consideration of expansion equations indicates a residual shock heating considerably less than that reported by Los Alamos. Means of measuring this experimentally are being analyzed. The feasibility of one possible method, using calorimetry of projectiles, is being checked.

6. CRATERING AND PENETRATION

This project is considered as the summation of all the others and consists of observing the impact process in selected systems and formulating theoretical models to describe them.

During this quarter, work was begun on a model describing the impact of a cylinder on a thin plate in order to predict the details of the generation of spray particles. This study is being coupled with an experimental investigation of target surface movement and spray-particle generation. No significant progress can be reported at this time except in the selection of an experimental scheme to observe surface motion. The method chosen is to observe the motion of a reflection in the polished surface of the target. The details of this method have been worked out in connection with a different problem.[3] The application to our problem should not be difficult.

7. CONCLUSIONS AND RECOMMENDATIONS

Progress is being made in measuring and understanding the phenomena occurring in high-velocity impact. The measurement of energy distribution has cast doubt on hydrodynamic models of cratering and indicated the necessity of carefully considering the energy involved in frictional and fusion processes. Some transient subsurface conditions have been measured during cratering. This opens the possibility of providing far better checks on theory than can be made from hole-size measurements. Progress has been made in developing analytical descriptions of material properties and wave motion in idealized systems. The application of this work to cratering and penetration models is being made.

---

[3] J. Wackerle, Jour. Appl. Phys., Vol. 33, p. 922, 1962.

It is recommended that work in all the areas listed above be continued with particular emphasis on application of results and ideas to models for thin-plate penetration.

Three reports are anticipated during the coming final quarter of the contract. They will be on energy partitioning, wave motion, and theory of thin-target penetration.